Clinical Biomechanics 57 (2018) 144–149

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Extensibility of the supraspinatus muscle can be predicted by combining shear wave elastography and magnetic resonance imaging-measured quantitative metrics of stiffness and volumetric fat infiltration: A cadaveric study

Hugo Giambini[a,*], Taku Hatta[b], Asghar Rezaei[c], Kai-Nan An[a,b]

[a] *Department of Orthopedic Surgery, Mayo Clinic, Rochester, MN, USA*
[b] *Biomechanics Laboratory, Division of Orthopedic Research, Mayo Clinic, Rochester, MN, USA*
[c] *Department of Physiology and Biomedical Engineering, Mayo Clinic, Rochester, MN, USA*

ARTICLE INFO

Keywords:
Rotator cuff tear
Ultrasound
Magnetic resonance imaging
Muscle properties
Tendon retraction

ABSTRACT

Background: A torn rotator cuff tendon will retract over time causing changes in muscle properties and decreasing its extensibility, or deformation. During surgery, large tensile loads are applied to bring the torn tendon to the footprint. Poor muscle extensibility and large tensile stresses at the repair might lead to gap formation or re-tear of the repair. A quantitative evaluation of muscle properties could be used to predict the extensibility of the supraspinatus (SSP) muscle.

Method: Magnetic resonance imaging (MRI)-measured volumetric fat fraction and shear wave elastography (SWE)-measured elastic modulus of the SSP muscle were obtained on seventeen cadaveric shoulders. Experimental extensibility and stiffness were then measured by axially pulling the tendon up-to 60 N. Univariate and multivariate analyses were used to determine the correlation and contribution of fat fraction and elastic modulus to experimental outcomes.

Findings: SWE moduli negatively correlated with SSP muscle extensibility ($r = 0.54$–0.58, $P \leq 0.0259$); fat fraction resulted in a positive correlation ($r = 0.69$, $P = 0.0021$). SWE measurements, solely, explained up to 34% and 33% of the variability in measured extensibility and stiffness, respectively. Fat Fraction, solely, explained 48% of the variability in extensibility and 36% of the variability in stiffness. These methods combined predicted up to 62% of the musculotendinous extensibility.

Interpretation: This study showed a comprehensive quantitative assessment of SSP muscle properties using SWE to estimate stiffness and MRI to measure fatty infiltration. The extensibility of the detached muscle/tendon unit was highly correlated to material properties of the muscle when these methods were used in combination.

1. Introduction

Pain, disability, and muscle atrophy are all sequela of rotator cuff tendon and muscle injury (Milgrom et al., 1995; Minagawa et al., 2013; Yamamoto et al., 2010). Patients who fail conservative treatment undergo individualized surgical procedures in order to reduce pain and restore shoulder motion and function (Caldwell et al., 1997; Gazielly et al., 1994; Harryman 2nd et al., 1991). Due to the nature of the lesion and muscle dysfunction over time, the detached rotator cuff tendon will retract causing a decrease in the supraspinatus (SSP) cross-sectional area, and changes in intramuscular fat infiltration, muscle stiffness, and compliance. These abnormal changes will lead to a deteriorated length-tension relationship of the muscle, representing the force the muscle will be able to generate at a specific length, and a decrease in its extensibility, or deformation. Consequently, during surgery, the muscle and tendon are subjected to large tensile loads in order to bring the torn tendon to the footprint (Berth et al., 2010; Ward et al., 2006). Poor muscle extensibility and large tensile stresses at the repair might eventually lead to gap formation or re-tear of the repair, as observed in about 17–57% of the surgical repaired cases (Bartl et al., 2012; Iannotti et al., 2013; Zumstein et al., 2008). Furthermore, poor muscle environment attributed to high content of fatty infiltration and characterized by muscle fiber atrophy, fibrosis, loss of muscle strength and poor vascularization, will decrease the regenerative potential of the tissue and repair (Gerber et al., 2007; Gladstone et al., 2007; Goutallier et al., 2003; Gumucio et al., 2014; Lohr and Uhthoff, 1990; Rathbun

---

* Corresponding author at: Mayo Clinic, 200 First Street SW, Rochester, MN 55905, USA.
E-mail address: giambini.hugo@mayo.edu (H. Giambini).

https://doi.org/10.1016/j.clinbiomech.2018.07.001
Received 18 October 2017; Accepted 2 July 2018

and Macnab, 1970).

In order to obtain a successful repair of the rotator cuff tear and achieve positive outcomes during the rehabilitation process, in addition to the routine clinical parameters measured using computed tomography (CT) and magnetic resonance imaging (MRI), a personalized quantitative assessment of muscle properties is necessary to better estimate the extensibility of the muscle as well as morphological parameters. Current clinical outcomes include the evaluation of gross muscle size and the presence and size of a tear, which can often be quantified; and a two dimensional (2D) qualitative evaluation of fatty infiltration. However, these methodologies and outcome measurements are mainly 2D, and more importantly, are unable to estimate the extensibility of the muscle-tendon unit and provide a quantitative evaluation of muscle properties.

Shear wave elastography (SWE) has been previously used to estimate the stiffness of skeletal muscles (Bouillard et al., 2011; Eby et al., 2015; Hug et al., 2015). Our group has previously implemented SWE to evaluate the properties of the SSP muscle under various positions and surgical conditions (Hatta et al., 2015b; Hatta et al., 2016a; Hatta et al., 2016b). More importantly, we have previously estimated the extensibility of the SSP musculotendinous unit by quantifying the stiffness (Hatta et al., 2017) and volumetric fat infiltration (Giambini et al., 2017) of the SSP muscle, independently, using SWE and MRI, respectively. In the current study, we hypothesized that a combined evaluation of muscle properties, namely stiffness and fatty infiltration, using SWE and MRI, respectively, could be used to predict the extensibility of the muscle, and obtain quantitative measurements of muscle properties that could be used to aid in pre-operative planning and post-surgical evaluation of rotator cuff tears.

2. Methods

2.1. Specimen preparation

Seventeen fresh-frozen cadaveric shoulders (mean age: 70 years.; range: 25–94 years.; 14 males, 3 females) were obtained after institutional review board approval from our institution. The shoulder specimens contained the scapula, the humerus cut at the mid shaft, muscles, and all other soft tissues including the skin. The specimens were kept frozen at −20 °C and thawed overnight at room temperature before imaging and testing.

2.2. Quantitative magnetic resonance imaging

After thawing overnight at room temperature the shoulder specimens were imaged with MRI, and volumetric fat fraction of the whole SSP muscle was quantified as previously described (Giambini et al., 2017). Briefly, scans were performed using a three dimensional (3D), isotropic 2-point Dixon MRI sequence (LAVA FLEX, TR/TE, 3.9/1.2; FOV, 30 cm; matrix, 200 × 200; slice, 1.5 mm; flip angle, 10°; bandwidth, 142.86 kHz; NEX, 1). Image datasets were imported into MATLAB (Rev. 2015b; The MathWorks, Natick, MA), obtaining real-valued fat and water images as previously described (Rydell et al., 2007). These new water and fat images were then corrected for intensity by the CIIC-method (Andersson et al., 2015), and exported as vtk-files to ITK-SNAP for segmentation of the SSP muscle (Yushkevich et al., 2006). The entire volume of the SSP muscle was manually segmented from both the water and the fat images and the volume masks was then imported back into MATLAB together with the associated water and fat datasets. Mean volumetric intramuscular fat fraction values were obtained based on Eq. 1 (Fig. 1A).

$$Fat\ Fraction\ (\%) = \frac{Fat\ Signal}{(Fat\ Signal + Water\ Signal)} \times 100 \tag{1}$$

2.3. Shear-wave elastography measurements

After imaging the shoulders with MRI, the scapula was disarticulated from the thorax and the humerus was cut at the level of the midshaft. The scapula and a fiberglass rod inserted into the humeral medullary canal were then secured in a custom-built experimental set-up (Hatta et al., 2015a). The scapula was fixed at 0° upward/downward rotation considered as a neutral position based on a recommendation by the International Society of Biomechanics (ISB) (Schwartz et al., 2014; Wu et al., 2005). The experimental set-up, designed to provide 6°-of-freedom motion of the glenohumeral joint in consistent motion paths, was used to place the humerus at 0° abduction for all measurements. All soft tissues including skin, subcutaneous fat, and muscles within the cut level were kept intact during this process.

SWE-measured elastic modulus [kPa] (as a surrogate for stiffness) of the SSP muscle was evaluated using a commercial ultrasound system (Aixplorer; Supersonic Imagine Ltd., Aix-en-Provence, France) with a linear array transducer (2–10 MHz; Supersonic Imagine, Ltd.) as previously described (Hatta et al., 2015b). A built-in-software was used to obtain the modulus for each region. Placement of the ultrasound transducer and measurement regions of the SSP muscle had been previously established (Hatta et al., 2015a; Itoigawa et al., 2015). Briefly, the SSP muscle was divided into 4 regions according to the muscle fiber orientation; anterior deep (AD), anterior superficial (AS), posterior deep (PD), and posterior superficial (PS). Measurements for each region were assessed independently on the plane parallel to the muscle fibers (Fig. 1B). SWE measurements were obtained repeatedly 9 times and the mean values were then calculated for each region (Hatta et al., 2015a). This process has previously shown excellent intra- and inter-observer reliability for all regions of the SSP muscle (Hatta et al., 2015a).

2.4. Musculotendinous unit extensibility measurement

Post ultrasound SWE measurements, all soft tissues and acromion from the shoulder specimens were removed. The presence of a rotator cuff tear, including width and length, were recorded, and the size of the tear was classified into small, medium, large, or massive (Post et al., 1983). The shoulders were then placed in a custom-built experimental set-up allowing for axial deformation of the SSP muscle and load/displacement recordings of the whole muscle-tendon unit (Fig. 2). The distal edge of the SSP tendon was cut from the greater tuberosity and the scapulae were rigidly fixed to the fixture. The SSP muscle/tendon junction edge was sutured and this suture was then looped around a linear potentiometer and clamped to a load cell. As the muscle was loaded, the linear potentiometer measured musculotendinous displacement data. To avoid repetitive loading that could damage the muscle fibers and affect the experimental outcomes, each muscle was axially pulled to 60 N manually using a pneumatic system for three cycles. This load has been previously implemented as a safe limit to avoid damaging the tendon or the muscle (Meyer et al., 2004; Meyer et al., 2006). The first cycle was used to precondition the muscles and data from the two additional cycles were analyzed. Mean displacement values at 60 N were then calculated for all shoulders from the two cycles. Muscle extensibility referred to the mean displacement at a 60 N load. Mean stiffness was evaluated from the linear region of the force/displacement curves.

2.5. Statistical analysis

JMP version 10.0.0 (SAS Institute Inc., NC) was used for statistical analysis. In all analyses, the outcomes were the measured extensibility and stiffness. Pearson correlation coefficient analysis was used to determine the correlation between fat fraction measured with MRI, or SWE elastic modulus from each muscular region of the SSP muscle, with the extensibility or stiffness outcomes obtained experimentally. For each univariate analysis a coefficient of determination (R^2) was